

F



MAJORANA NEUTRINOS  
?

A DECISIVE PROJECT

AT  
>TeV  $\mu^{\pm} \mu^{\pm}$  COLLIDERS

HEMC  
Montauk

Now for a change of pace: Imagine there are Majorana neutrinos  $N_\eta$  so heavy that they have escaped detection so far:

## VERY HEAVY NEUTRINOS WITH MAJORANA NATURE IN THE TeV RANGE

- They might have very attractive features — "explain" the great mass differences inside higher-symmetry supermultiplets.
- ... Establish the Majorana character of neutrino mass terms in the mass matrix
- ... furnish definitive experimental signals well above all imaginable backgrounds
- ... utilize the {<sup>Muon</sup> Linear} Collider for a key experiment on neutrino mass.

## USEFULNESS OF MUON COLLIDER FOR $N_m$ SEARCH:

- The symmetry structure of heavy singlets could couple  $N_m^i$  differently to  $e, \mu$ :  
 $U_{ei} = ?$
- The strong energy dependence of  $\sigma(\bar{e}\bar{e}) \rightarrow W^+W^-$   $\sim s^2$  could make the energy range of the muon collider vital
- If  $m(N_m) \gtrsim 1.5$  TeV, again, the energy range will help

## WEAKNESS OF MUON COLLIDER IN $N_m$ SEARCH:

- The absence of good control over the polarization parameters makes signal / background identification harder

FOR DEFINITENESS, WE WORK IN A MINIMAL  
EXTENSION FRAMEWORK OF THE STANDARD MODEL:

{ 3 small  $\nu$  masses  
(may be  $= 0$ )  
 $N' \geq 2$  heavy neutrinos

FOR A TOTAL OF  $\geq 9$  LEFT-HANDED FIELDS

$$\begin{pmatrix} \nu_1 & \nu_2 & \nu_3 & N_1 & N_2 & \dots \\ e^- & u^- & \tau^- & e^+ & \mu^+ & \tau^+ \end{pmatrix}$$

SUCH MULTIPLETS ARE COMMON TO SEVERAL  
MODELS, e.g.,

UNIFYING GROUPS FROM CHAIN

$$E(6) \rightarrow SO(10) \rightarrow \dots$$

WITH 3 FAMILIES OF 27 REPS OF E6

WE CALL THIS THE MINIMAL MASS-GENERATING CASE  
WITH  $N_1, N_2$  BEING THE LEAST MASSIVE HEAVY  
NEUTRINOS WITH MASSES  $m_1, m_2$

→ LARGEST OF INVARIANT HEAVY-LIGHT  
MIXING ANGLES:

$$(m_t \approx 60 \text{ GeV})$$

$$|\alpha_{\max}| \leq \frac{m_t^{(u)}}{\sqrt{m_1 m_2}}$$

C.A.H., Peter Minkowski

BEING ABLE TO CHOOSE INCOMING ELECTRON POLARIZATION CAREFULLY, WE WERE ABLE TO EVALUATE REALISTIC CASES FOR GIVEN CHIRAL COUPLINGS:

WE TAKE 3 LIGHT NEUTRINOS  $\nu_i$   $i = 1 \dots 3$   
3 HEAVY  $N_i$   $i = 4 \dots 6$

AND FIX THESE 6 ( $i = 1 \dots 6$ ) WEAK INTERACTION EIGENSTATES  
INTO MASS EIGENSTATES

$$\begin{array}{ll} \hat{\nu}_\alpha & \alpha = 1 \dots 2 \\ N_\alpha & \alpha = 3 \dots 6 \end{array}$$

BY MEANS OF A  $6 \times 6$  MATRIX  $U_{L\alpha}$

$$\nu_i = \bar{U}_{i\beta} \hat{\nu}_\beta \quad \hat{\nu}_\alpha = U_{i\alpha} \nu_i \quad \left. \begin{array}{l} i \\ \alpha \\ \beta \end{array} \right\} = 1 \dots 6$$

WE OBTAIN  $U_{i\alpha}$  FROM THE LAGRANGIAN

$$L_M = \frac{1}{2} (\bar{\nu}_i^\tau \epsilon_{\delta\gamma} M_{ij} \nu_j^\delta + h.c.)$$

BY SUBSTITUTING  $M = U m_D U^{-1}$   
( $m_D$  IS DIAGONAL)  $\rightarrow M_{ij} = U_{i\alpha} (m_D)_\alpha U_{j\alpha}$

$\rightarrow$  MAIORANA MASS MATRIX ( $6 \times 6$ )

$$M_{ij} = \begin{pmatrix} 0 & M^T \\ M & 0 \end{pmatrix}$$

↑ major Majorana mass term,  $O(1TeV)$

IS THE PROCESS

$$e^+ e^- \rightarrow W^+ W^- \nu_L \bar{\nu}_L$$

A SERIOUS BACKGROUND TO THE LEPTON-  
NUMBER PROCESS WITH  $\nu_R$  EXCHANGE?

NO?

- $\nu_L \bar{\nu}_L$  GENERALLY ESCAPE WITH  
- HALF THE C.M. ENERGY  
 $\rightsquigarrow E_{CM}$  CUTS WILL DO THE TRICK.
- ALL BACKGROUND GRAPHS COUPLE  
A GAUGE BOSON TO  $e_L$   
 $\rightsquigarrow$  CHANGING THE BEAM POL'N  
WILL ELIMINATE ALL 9 TOPOLOGIES  
(in the absence of  $W_R$ )

WE WORK IN THE KINEMATIC REGIME

$$2m_W \ll \sqrt{s} \ll M,$$

WITH COUPLING/MIXING PARAMETERS (FOR THE ELECTRONS)

$v_{eA}$

$$A = 1, 2, (\dots)$$

THE OVERALL NEUTRINO MASS MATRIX IS THEN

$$M = \begin{pmatrix} & \begin{matrix} 1 & 2 & 3 \end{matrix} & \begin{matrix} 4 \\ 5 \\ 6 \end{matrix} & \dots \\ \begin{matrix} 1 \\ 2 \\ 3 \end{matrix} & 0 & \mu^T & \\ \hline & \mu & M & \end{pmatrix}$$

AND

$$M = U m_D U^T$$

↳ diagonal matrix

$$m_1, m_2, m_3, M_1, M_2$$

INCLUDING ALL KINEMATIC INTEGRATIONS, WE ARRIVE AT CROSS-SECTIONS

$$\sigma(e^- e^- \xrightarrow{\text{N}} \omega^- \omega^-) \approx \frac{1}{\pi^2 T_W^2} \left(\frac{s}{\pi^2}\right)^2 \left(\frac{h_e}{4\pi}\right)^2$$

mixing parameters

$$\pi = \sqrt{\pi_1 \pi_2} \gtrsim 1-10 \text{ TeV}$$

THESE CROSS-SECTION ESTIMATES ARE

- CONSERVATIVE IN ASSUMING ~ EQUAL MIXING FOR  
 $\mu, e$  WITH HEAVY NEUTRINO ( $E, M$ ) STATES

⇒ LEAD TO RESPECTABLE EVENT RATES.

FOR THE STANDARD  $10^7$  second "YEAR":

SCENARIO	$(\gamma^{(N)})$	$2 \times 10^{-4}$	$5 \times 10^{-3}$
NLC ( $\mathcal{L} = 10^{33}$ )		.01	6
	( $\mathcal{L} = 10^{34}$ )	.1	60
TLC ( $\mathcal{L} = 10^{34}$ )		2	1,000
	( $\mathcal{L} = 10^{35}$ )	20	10,000

EVENTS / YEAR

→ FINAL-STATE RECOGNITION:

- BACK-TO-BACK GEOMETRY

(INCLUDING RISING MOMENTUM)

⇒ A HUGE HELP!

A DETECTOR WITH  $10^\circ$  OPEN CONES WILL NOT

HAVE SERIOUSLY IMPAIRED EFFICIENCY.

IF ... "BACKGROUNDS" ARE  
MANAGEABLE ...

IS THIS COMPATIBLE WITH EVIDENCE

$\gamma^N$

ON LEPTON FLAVOR VIOLATION?  
UNIVERSALITY

A COMPARISON OF

$$\bullet \quad \mu^- \rightarrow e^- \bar{\nu}_e \bar{\nu}_{\mu} \leftrightarrow (A, z) \rightarrow (A, z+1) e^- \bar{\nu}_e$$

$$\bullet \quad \pi^\pm \rightarrow \mu^\pm \bar{\nu}_\mu \leftrightarrow \pi^\pm \rightarrow e^\pm \bar{\nu}_e$$

$$\bullet \bullet \bullet \quad \bar{\nu} \rightarrow e^- \bar{\nu}_e \bar{\nu}_\mu \leftrightarrow e^- \rightarrow \bar{\nu}_e \mu^- \bar{\nu}_\mu \\ \rightarrow \bar{\nu}_e e^- \bar{\nu}_\mu$$

PERMITS A CHECK ON UNIVERSALITY

$\rightarrow$  NO SEVERE LIMIT ON  $|\gamma^{(n)}|$

PARAMETERIZATION OF

$$\mu^\pm \rightarrow e^\pm \gamma, e^\pm e^+ e^-$$

$$\tau^\pm \rightarrow \mu^\pm \gamma, e^\pm \gamma$$

$$n(A, z) \rightarrow e(A, z)$$

PERMITS SIMILAR ANALYSIS OF

LEPTON FLAVOR VIOLATION

$n \rightarrow e\gamma, \underline{eee}$  IS MOST RESTRICTIVE

AND GIVES THE LOWER LIMIT

... ~~so~~, IF WE ARE LUCKY,

$$e^- e^- \rightarrow \omega^- \omega^-$$

MAY BE THE REACTION  
WHERE WE WILL LEARN  
ABOUT

THE MAJORANA CHARACTER  
OF NEUTRINOS

THE MECHANISM THAT  
MIXES NEUTRINO FLAVORS

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BUT IF THE HEAVY  $N_H$  STATES  
ARE TOO MASSIVE FOR THE NLC / TESLA,

THE MUON COLLIDER WILL LIKELY  
SEE THEM